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Center for Fire Research
National Engineering Laboratory
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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*

Jordan J. Baruch, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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FIRE ACCIDENT SIMULATIONS WITH APPAREL FABRICS

A. W. Meierhoefer[1], E. Braun, J. F. Krasny, and R. D. Peacock

Abstract

The objective of the work described here was to continue earlier garment burn simulations and to establish further background for the estimation of the relative burn injury potential of flammable apparel fabrics. The apparatus used was the Apparel Fire Modeling Apparatus (AFMA). The AFMA is a semi-cylinder almost completely covered with heat sensors. It simulates part of a human leg or torso. Fabrics can be burned on the AFMA in the free-hanging mode or can be brought into contact with its surface after a small amount of heat is sensed by the AFMA. The burn injury potential of the fabrics can be evaluated by such heat transfer characteristics as the total heat transferred to the AFMA and the area of the AFMA which would be susceptible to a second-degree burn, as well as the rate of increase of this injury area. The results are related to fiber content, and weight and construction of the fabrics. The fabrics used were selected from a series used in the Cooperative Program on Apparel Flammability sponsored by the American Textile Manufacturers Institute.

Key words: Accident; apparel; burn injury; clothing; fabric flammability; fabrics; fire; garments; heat transfer; injury potential; simulation.

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[1] This work was done while Dr. Meierhoefer served as an NBS Research Associate representing the Man-Made Fiber Producers Association. Dr. Meierhoefer's current address is the American Enka Company, Enka, North Carolina.

1. INTRODUCTION

The simulation of fire accidents has been recognized as an important experimental approach to measuring the burn injury potential of fabrics and garments. The results of such experiments are useful in the development of meaningful pass-fail criteria based on laboratory flammability tests.

Previous simulation work has usually involved the use of a mannequin. The underlying thought is that mannequins provide a reasonable approximation of apparel fire accidents in which the complex shape of the human body plays a role. Many simulations using simple mannequins have employed photographic techniques [1][2] or simple heat sensors [2,3] to estimate the burn injury potential of garment assemblies. More completely instrumented mannequins, such as Thermo-Man, have been used to establish detailed estimates of the injury potential of garments in stationary situations [4]. The lack of movement in these experiments removes one key element in simulations since some garment and body movements are generally associated with actual accidents.

Some simulation experiments which cover a variety of defensive actions leading to extinguishment are described in the literature. Work sponsored by the Consumer Product Safety Commission at the University of Maryland and the National Bureau of Standards covered such extinguishing modes as slapping [5,6], airflow, contact with heat sinks, and oxygen depletion [6]. LeBlanc has also investigated airflow and slapping [7].

The Apparel Fire Modeling Apparatus (AFMA) which was designed at the National Bureau of Standards and first used by Zawistowski, et al., is an attempt to include movement leading to body-fabric contact in the fire accident simulation [8]. Basically, the AFMA is a semicylinder which is almost completely covered with heat sensors. It simulates a

[2] Numbers in brackets refer to the literature references listed at the end of this paper.

leg or a torso. The specimen is ignited while hanging at some distance from the AFMA surface. If it is allowed to remain in the original position, the experiment is called "free-hanging." In other experiments called "reaction," the AFMA, upon sensing a certain temperature rise, reacts by tilting and making contact with the burning specimen. It is thus possible to simulate two extremes of what could happen in real-life garment fires: the uninterrupted, free-burning of a loosely fitting garment and the behavior of a garment after it makes contact with a part of the body which may serve to absorb heat and to exclude oxygen from one side of the fabric. This contact frequently leads to extinguishment of the burning fabric.

While extinguishment of burning fabrics upon contact with skin has been observed during in-vivo experiments [3], no claim is being made that the present work where the contacting surface consists of copper sensors would give the same results as if skin had been exposed. However, the relative ranking of the fabrics may be approximately the same for the real-life fabrics and the present experiments independent of the heat transfer properties of the medium receiving the heat.

The objective of this work was to continue earlier garment burn accident simulations [8] and to establish further background for estimation of fabric burn injury potential. The fabrics used were chosen from a larger number of fabrics which were used in the Cooperative Program on Apparel Flammability sponsored by the American Textile Manufacturers Institute (ATMI) [9]. In this effort, 15 laboratories performed flammability tests or accident simulations with 65 fabrics furnished by ATMI. The present report deals only with the results of the AFMA simulations; future reports will relate these results to other laboratory tests and Thermo-Man burn accident simulations.

2. EXPERIMENTAL

2.1 The Apparatus

The AFMA is a vertically-mounted semicylinder, 60 cm (24 in) high and 18 cm (7 in) in diameter (see figure 1). The lower end of the semicylinder is mounted on a fixed pivot which allows the AFMA to move through an arc of approximately 20°. A fabric is mounted on a frame from the top of the semicylinder, and ignited. At some point, the semicylinder "reacts" (moves to a vertical position), bringing the burning fabric into contact with the surface. The surface of the semicylinder is almost completely covered by blackened copper sensors. The sensors are 7.6 x 2.5 cm, and are separated by 0.3 cm strips of mineral board. Heat transferred to each sensor is recorded every 3 seconds. A more detailed description of the AFMA can be found in an earlier publication [8].

Before work on the present series was started, three modifications of previous procedures were introduced: a change in the criterion for initiation of the reaction, closing the specimen on the top and sides so that heat would be trapped as in an actual garment, and introduction of the "injury area" concept.

The monitoring circuit allows the AFMA to react to a specific heat output rather than employing manual initiation for the reaction at a specific time from ignition or flame spread distance. This monitoring circuit follows the temperature of four of the AFMA sensors located at various heights in the center row. When any of these four sensors registers a temperature rise of 5° C (which would probably be perceived by a human), the AFMA "reacts"; i.e., swings, causing contact of specimen and AFMA surface. The choice of a 5° C temperature rise is somewhat arbitrary, but is probably in the range perceived by a reasonably alert person.

Another change was in the specimen configuration in order to make it simulate a garment more closely. A backing fabric and a belt on top were

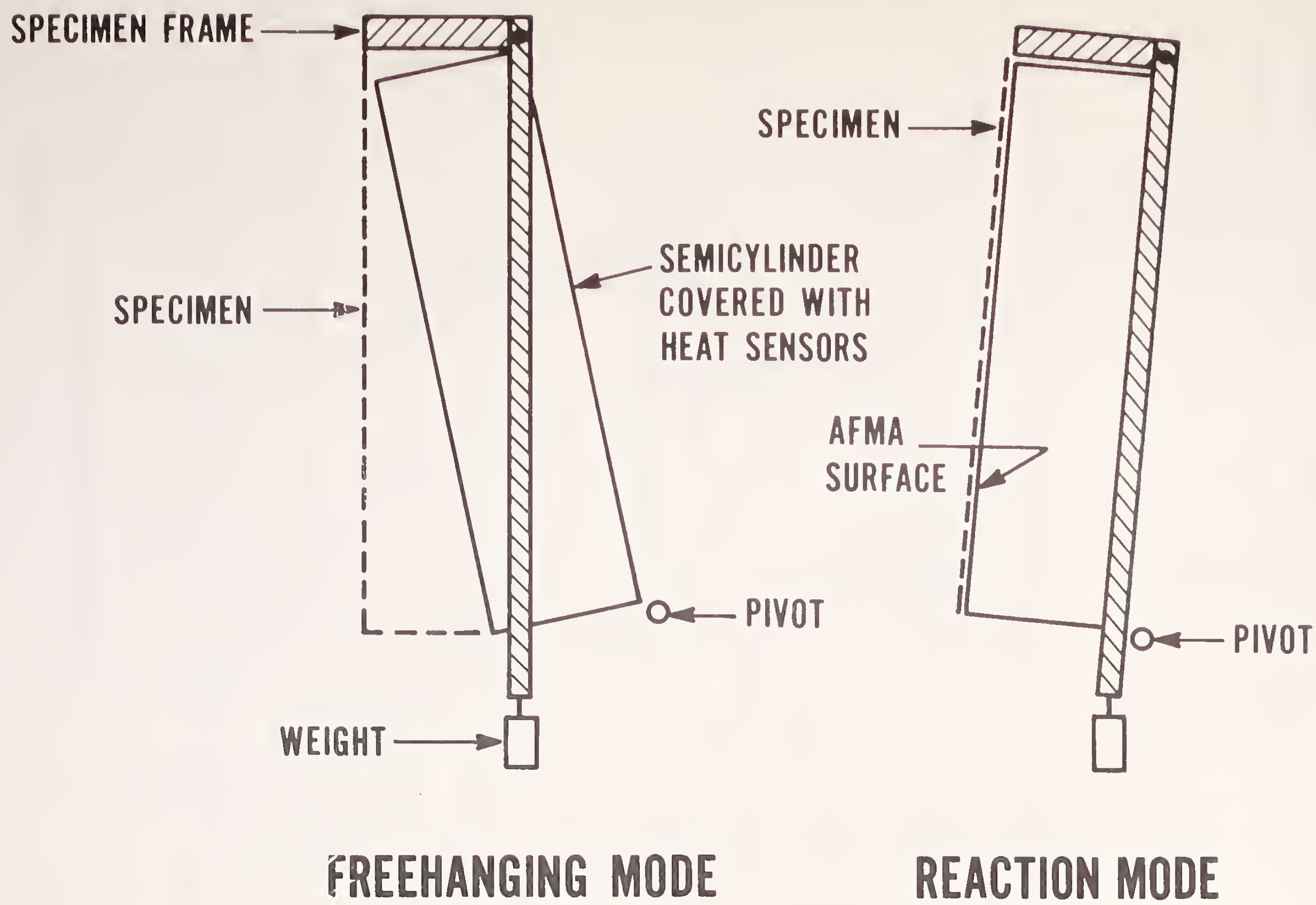

Figure 1. Schematic view of AFMA

added, so that the specimen was part of an envelope enclosing the AFMA rather than being open on the top and sides. The backing was a piece of Nomex[R] aramid fabric draped behind the AFMA and clamped to the specimen frame. The wire "belt" was placed around the top of the specimen so it contacted the AFMA top. These changes were important to minimize heat loss to the surroundings and to create a closed system resembling a garment.

2.2 Data Acquisition and Computation

The data acquisition and computations were carried out similar to the previous AFMA work [8] except for introduction of the "injury" concept. The heat sensors of the AFMA surface were scanned every 3 seconds and the thermocouple outputs were recorded on magnetic tape. Subsequent processing using NBS computer facilities gave equivalent heat flux values for each sensor at 3-second intervals. The general calculations involved determining the sensor temperature from the measured thermocouple millivolt output and then converting this to the quantity of heat transferred using heat constants for each sensor arrived at by calibration as described in an earlier report [8].

In addition to the heat transferred to each sensor, an estimation of "injury" was made for each sensor. The injury described here is an estimated incipient second-degree burn or deeper. The estimation is based on the work of Derksen [10]. He exposed blackened rat skin to square wave radiative heat at various rates, and established the relationship between total amount of heat and rate at which it was received, to produce a second-degree burn. Stoll [11] showed this relationship to hold true for human skin and convective as well as radiative heat. Figure 2 shows the Derksen curve, and a typical heat received vs exposure time curve for one AFMA sensor. The AFMA is considered "injured" where the two curves intersect. The number of injured sensors was determined for each 3-second interval from the time of ignition, and this was used to calculate the "injury area" reported in the tables. This injury area

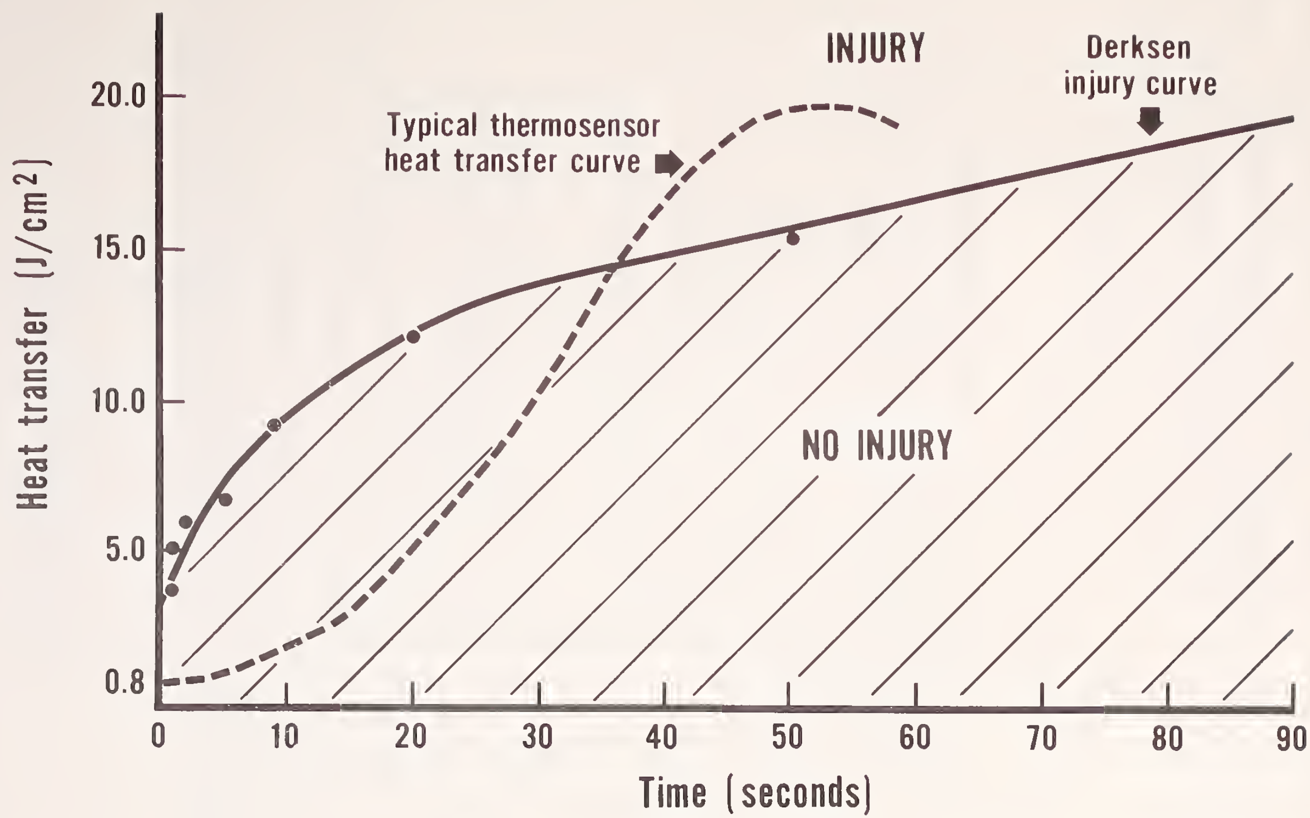

Figure 2. Time-heat curve for one AFMA sensor and Derksen injury curve

concept does not differentiate between second- and third-degree burns. However, consideration of the injury area along with the total heat delivered to this area permits a comparison of the depth of injury which may be caused by the various fabrics. It must also be noted that the AFMA heat sensors are blackened copper with thermal characteristics quite different from those of human skin. The injury concept is thus only an approximation but, when used for comparative purposes, should permit rough ranking of fabrics in terms of their burn injury potential.

2.3 Fabrics

The fabrics used in the AFMA simulation work were those supplied by the American Textile Manufacturers Institute in the Cooperative Apparel Fire Accidents Flammability Program [9]. The fabrics were representative of the range of fiber and fabric types presently in common use but also included a few experimental fabrics. The 58 fabrics used in this work are described in tables 1 and 2. Table 1 shows the fabrics which did not produce enough heat to cause reaction by the AFMA; i.e., did not raise the temperature of four sensors located at various heights in the center row of the AFMA more than 5° C. Table 2 lists the fabrics which caused reaction, arranged by fiber content, and within each fiber content group, by increasing weight. There were nine 100% cotton fabrics; 14 polyester/cotton blends varying in polyester/cotton ratios from 76/24 to 15/85; seven fabrics containing acetate or triacetate alone or in blends with nylon; nine fabrics containing acrylic or modacrylic fibers, some blended with polyester; 13 fabrics containing thermoplastic fibers, nylon, or polyester; and five fabrics containing wool. Constructions ranged from lightweight wovens to denims, corduroys, terry towels, and included various knits.

2.4 Simulation Procedure

The samples were prepared and conditioned in a room maintained at approximately 23° C and a relative humidity of 40%. The samples were then

Table 1. Fabrics which cause no reaction in AFMA simulation

ATMI Number	Description	Weight g/m^2	Weight (oz/yd^2)	Total Heat J
11	100% PET Woven	80	2.3	662
13	" " " FR	130	3.8	272
7	" " Knit	190	5.7	942
9	" " "	240	7.2	360
8	" " "	240	7.2	214
4	" " "	245	7.3	3488
5	" " Woven	270	8.0	398
14	" Nylon-6 Knit	30	0.9	176
15	" " "	80	2.4	502
68	" Nylon Knit	90	2.7	193
41	71/29 Modacrylic/Acrylic Knit	155	4.5	473
43	" " "	295	8.7	343
21	100% Wool Woven	205	6.0	377
54	" " " FR	195	5.7	452
53	" " " "	270	8.0	285

Table 2. Heat transfer characteristics and igoition and reaction times of fabrics which caused reactioo

ATMI[a] No.	Fabric Description	Weight		Total Heat[b]		Injury Area[b] (Reaction)	Max. Rate of Increase[b] of Injury Area		Ignition Time	Reaction Time
				Freehanging	Reaction		Freehanging	Reactioo		
		gm/m^2	oz/yd^2	J	J	cm^2	cm^2/s	cm^2/s	s	s
A. 100% Cotton Fabrics										
66	Flanoel	130	3.9	59500/3	10700/3	426/2	88/4	84/4	2	16
19	Chambray	140	4.2	58100/3	14500/4	639/3	103/4	64/4	1-2	16
18	Rib knit	260	7.6	80300/4	5000/2	310/2	60/3	71/4	3	27
20	Twill	270	8.0	88800/4	7900/3	129/1	58/2	52/3	2	35
64	Sateeo	280	8.3	91100/4	8100/3	265/2	77/3	45/2	3	33
63*	Sateen, low-level FR	300	8.9	1900/1	3800/1	369/3	19/1	51/3	3	14
17	Deoim	375	11.0	106600/4	4600/2	210/2	70/3	45/2	3	55
62	Corduroy	375	11.0	106900/4	6900/2	234/2	52/2	32/2	3	55
52	Denim	490	14.5	113900/4	5300/2	239/2	6/1	32/2	3	79
B. Polyester/Cellulose Blends Polyester/Cotton Blends										
29	65/35 Broadcloth	85	2.5	34700/2	12400/3	735/4	116/4	90/4	.5-1	9
55	74/26 "	90	2.6	34600/2	22600/4	1020/4	84/4	71/4	.5	12
25	52/48 "	105	3.1	48600/3	11000/3	603/3	84/4	77/4	2	14
31	65/35 "	110	3.3	52800/3	10500/3	639/3	116/4	97/4	1	10
30	64/36 "	165	4.9	75300/3	13800/3	471/3	77/3	64/4	1-2	36
26	48/52 Jersey knit	165	4.9	66600/3	6400/2	342/3	52/2	71/4	1	36

[a] Asterisk next to ATMI No. indicates bottom igoition; fabrics did not ignite with paper tab held on fabric surface.

[b] Number after slash indicates quartile; e.g., 59500/3 meaos result is in third (oext to highest) quartile.

Table 2. Heat transfer characteristics and ignition and reaction times of fabrics which caused reaction (continued)

ATMI[a] No.	Fabric Description	Weight		Total Heat[b]		Injury Area[b] (Reaction)	Max. Rate of Increase[b] of Injury Area		Ignition Time	Reaction Time
				Freehanging	Reaction		Freehanging	Reaction		
		gm/m^2	oz/yd^2	J	J	cm^2	cm^2/s	cm^2/s	s	s
B.	Polyester/Cellulose Blends Polyester/Cotton Blends									
24	50/50 Twill	205	6.1	84000/3	6200/2	270/3	77/3	39/2	2	42
60	48/52 Double knit	260	7.6	80000/3	30500/4	839/4	52/2	58/3	2	20
33	65/35 Twill	260	7.7	90000/4	4500/2	213/2	32/1	45/2	2	68
32	54/46 Oxford	280	8.2	92100/4	3700/1	248/2	58/2	29/2	2-3	61
48	22/78 Terry, single face	290	8.6	75500/3	19500/4	555/5	84/4	45/2	.5	30
34	18/82 Corduroy	320	9.4	95900/4	10300/3	497/3	39/1	59/3	3	32
28	49/51 Twill	325	9.6	89800/4	5300/2	213/2	52/2	26/1	3	46
56	15/85 Terry, double face	325	9.6	91000/4	96900/4	1420/4	88/4	29/1	.5	40
	Polyester/Rayon Blend									
39	49/51 Broadcloth	90	2.7	23400/2	9500/3	426/2	79/4	64/4	1	9
C.	Acetate, Triacetate, and Blends with Nylon									
36	81/19 Ac./Nylon tricot knit	90	2.7	7800/1	8400/3	684/4	71/3	45/2	.5-1	13
35	81/19 " " "	95	2.8	12000/2	14000/4	735/4	52/2	58/3	.5-1	12
37	65/35 Triace./Nylon tricot	100	2.9	8300/1	16400/4	710/4	26/1	51/3	1	16
38	65/35 " "	100	3.0	10600/1	11100/3	542/3	39/1	39/2	1	16
57	100% Triace. tricot	115	3.4	5600/1	1900/1	28/1	58/2	7/1	1	32

[a] Asterisk next to ATMI No. indicates bottom ignition; fabrics did not ignite with paper tab held on fabric surface.

[b] Number after slash indicates quartile; e.g., 59500/3 means result is in third (next to highest) quartile.

Table 2. Heat transfer characteristics and ignition and reaction times of fabrics which caused reaction (continued)

ATMI[a] No.	Fabric Description	Weight		Total Heat[b]		Injury Area[b] (Reaction)	Max. Rate of Increase of Injury Area[b]		Ignition Time	Reaction Time
				Freehanging	Reaction		Freehanging	Reaction		
		gm/m^2	oz/yd^2	J	J	cm^2	cm^2/s	cm^2/s	s	s
C. Acetate, Triacetate, and Blends with Nylon										
65	100% Ac. sateen (woven)	175	5.1	35200/2	29100/4	948/4	88/4	90/4	1	15
58	79/21 Triace./Nylon 6 velour knit	210	6.2	19800/2	16600/4	710/4	39/1	26/1	2	24
D. Acrylics, Modacrylics, and Blends with Polyester										
69	100% Acrylic knit	285	8.4	79500/3	50800/4	1000/4	97/4	58/3	-	28
40	48/52 Pet/Acr. jersey knit	190	5.6	9600/1	3300/1	213/2	13/1	7/1	3	54
59	45/55 " double knit	280	8.3	50500/2	30100/4	735/4	64/3	31/2	2	16
42*	51/49 Modacr./Acr. jersey	155	4.5	24100/2	5400/2	213/2	52/2	32/2	3	22
44*	" Modacr. Swiss pique knit	305	9.0	41300/2	4150/1	106/1	52/2	13/1	-	25
46*	23/39/38 Pet/Modacr./Acr. Swiss pique	325	9.6	43700/2	3500/1	129/1	45/2	19/1	-	23
45*	25/54/21 Pet/Modacr./Acr. Swiss pique	345	10.2	6500/1	780/1	∿0/1	13/1	∿0/1	-	32
E. Polyester and Nylon										
3*	100% Pet sharkskin	180	5.3	860/1	1910/1	50/1	10/1	∿0/1	-	50
6*	100% Taffeta	60	1.8	2500/1	1120/1	110/1	5/1	13/1	-	57
16	100% Nylon 66 taffeta	90	2.7	4100/1	4600/2	100/1	6/1	7/1	-	120

[a] Asterisk next to ATMI No. indicates bottom ignition; fabrics did not ignite with paper tab held on fabric surface.

[b] Number after slash indicates quartile; e.g., 59500/3 means result is in third (next to highest) quartile.

Table 2. Heat transfer characteristics and ignition and reaction times of fabrics which caused reaction (continued)

ATMI[a] No.	Fabric Description	Weight		Total Heat[b]		Injury Area[b] (Reaction)	Max. Rate of Increase[b] of Injury Area		Ignition Time	Reaction Time
				Freehanging	Reaction		Freehanging	Reaction		
		gm/m^2	oz/yd^2	J	J	cm^2	cm^2/s	cm^2/s	s	s
F. Wool Blends										
67*	55/45 PET/Wool twill	270	7.9	32200/2	280/1	~0/1	52/2	~0/1	3	25
61*	16/84 Nylon 6/Wool flannel	300	8.8	2100/1	1900/1	128/1	26/1	19/1	3	28

[a] Asterisk next to ATMI No. indicates bottom ignition; fabrics did not ignite with paper tab held on fabric surface.

[b] Number after slash indicates quartile; e.g., 59500/3 means result is in third (next to highest) quartile.

mounted on the AFMA. A paper tab was placed on the front of the specimen, 12 cm (4.75 in) from the bottom edge. The back fabric and the wire belt on the top were then attached. Upon ignition of the tab, a stopwatch was started to determine the time until the temperature of one of the four monitored sensors increased by 5° C. This was called the reaction time.

At the instant of ignition of the tab, the data acquisition system was started and allowed to scan the heat sensors at 3-second intervals during the burning of the fabric and for about 15 seconds after the last evidence of fabric combustion. For those fabrics which would not ignite with surface ignition, a second attempt was made by ignition at the bottom edge.

After each experiment, the AFMA was cleaned, any adhering char or thermoplastic melt removed, and allowed to cool. The general procedure was to let all heat sensors cool until the potential from the thermocouples was 0.02 mv or less.

Samples were tested either in the free-hanging mode or the AFMA was allowed to react to make fabric contact when the temperature on any one of four sensors rose 5° C, as discussed earlier.

At the end of the series of experiments, the magnetic tape was processed to give the injury and heat data for each sensor. Copies of the raw data and the computer programs are on file at NBS.

In addition to determining injury area, and total heat received by this area, a measure of the probability of ignition of the fabrics was desired. Ignition time was measured on the Mushroom Apparel Flammability Tester (MAFT) [12]. Cylindrical specimens were exposed to a methane flame at a point 10 cm above their bottom edge. The ignition time was not measured for fabrics with low heat transfer characteristics.

3. RESULTS AND DISCUSSION

In the AFMA simulations, fabrics fall into two general classes, those which caused the AFMA to react and those which did not. The determination of "reaction" was by heat transfer, so those which caused no reaction either did not ignite under the above described ignition procedure, or, if they did, transferred very little heat. Several examples were noted where large areas of fabric were destroyed but too little heat was transferred to the AFMA surface to initiate reaction.

Table 1 lists those fabrics which did not transfer enough heat to cause AFMA reaction. Included in this group are all but three of the 100% nylon and polyester fabrics; the two modacrylic/acrylic blends with highest modacrylic content; and one untreated and two FR treated wool fabrics. The only measurement made for these samples was the total heat transferred to the AFMA sensors during the experiment which includes the heat from the paper ignition tab. For all of these, ignition was attempted both on the surface and from the bottom edge.

Table 2 shows fabric construction and the results of the free-hanging and reaction simulations for the fabrics which caused a reaction by the AFMA. Fabrics which did not ignite with a burning paper tab attached and were ignited at the bottom edge to the surface are indicated by an asterisk next to the ATMI number in the table.

Figure 3 shows injury area as a function of exposure time for the free-hanging and reaction modes for a lightweight, polyester/rayon fabric (No. 39). The first reading of heat rise on the AFMA was at about 7 seconds; at 9 seconds, 5° C heat rise was registered and the AFMA reacted to make contact with the burning specimen. After this, the area of the simulated body which was considered to be the "injury area" (i.e., it received heat in the amount and at the rate which, according to Derksen, would cause a second-degree burn) increased rapidly. Soon afterwards, the rate at which the injury area increased slowed down and almost leveled

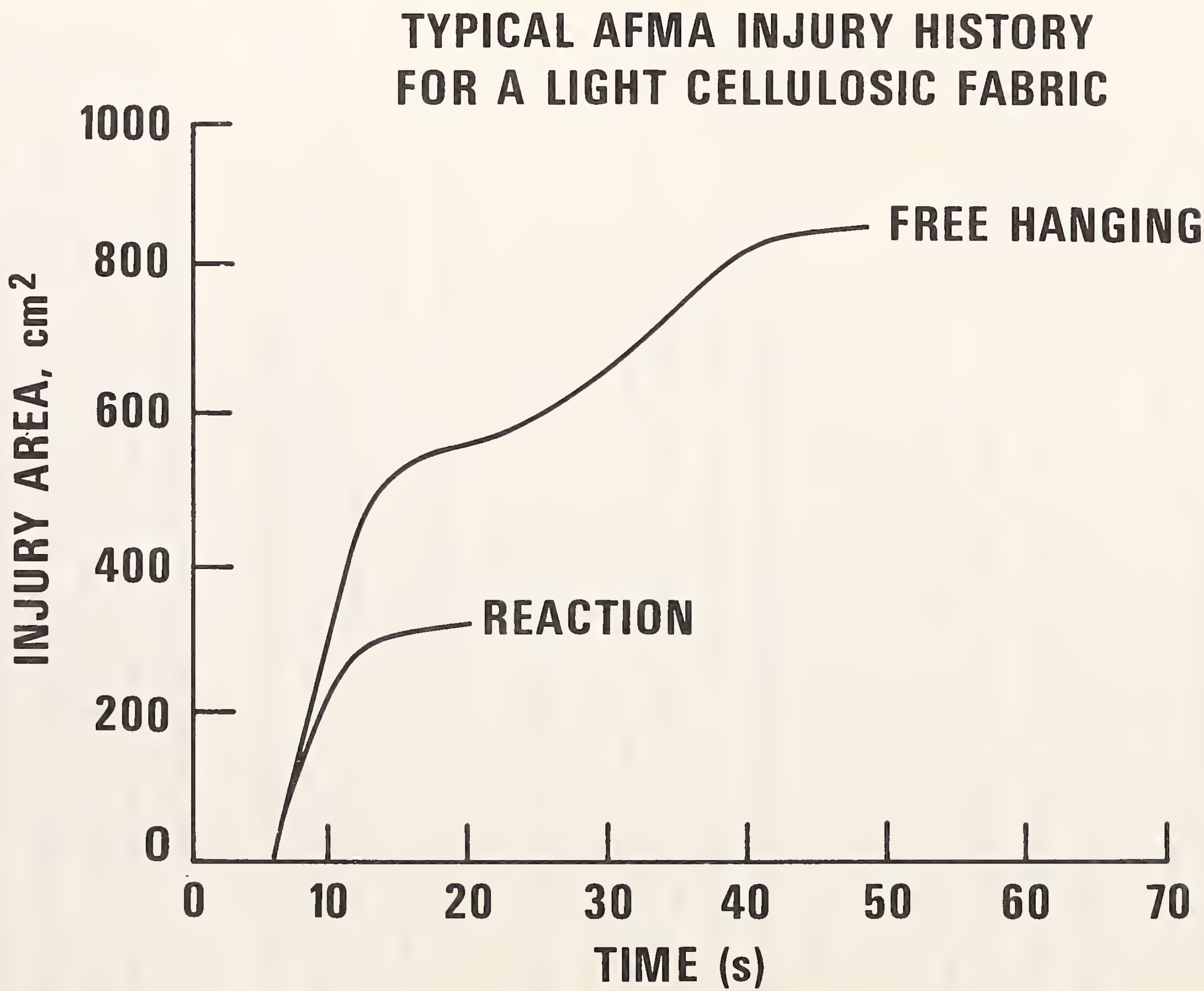

Figure 3. Injury area-time history for 90 g/m^2 (2.7 oz/yd^2) PET/rayon fabric (no. 39)

out at about 12 seconds, indicating extinguishment. The free-hanging specimen transferred heat at the initial rate for about the same time. When the flames reached the top and started to spread horizontally, the rate of injury area increase slowed down. The total injury area caused by the free-hanging specimens was about 2-1/2 times that of the reaction specimen. (About 30% of the AFMA area could be considered injured in the reaction mode, and 75% in the free-hanging mode.)

Two columns of table 2 show the total heat received by the AFMA during the whole duration of the burns for the free-hanging mode and for the reaction mode. Where the fabric extinguished soon after reaction (because of the heat sink effect and the exclusion of oxygen by the AFMA surface), the reaction heat was lower than the free-hanging heat. In some cases the reaction heat was higher, indicating that either no (or slow) extinguishment took place or that more heat was transferred to the AFMA because of closer specimen-AFMA surface distance than in the free-hanging mode (e.g., fabric 5b, terry cloth, and several acetate fabrics, group 1, table 2).

The next column of table 2 shows "injury area," that AFMA area considered to have undergone the equivalent of an incipient second-degree or deeper burn, as discussed earlier. Only the reaction mode results are listed because the free-hanging specimens were burned almost entirely and there was little difference in injury area results between the various fabrics.

The "maximum rate of injury area increase" in the free-hanging and reaction modes is the maximum increase in injury area measured during any 3-second period during the burn. For many free-hanging fabrics, especially cellulosic fabrics (those which contain rayon or cotton, alone or in blend with other fibers) which burn primarily upward, the flame spread rate may increase till the fabric burns a considerable distance from the point of ignition before it levels out [13]. The values reported here for free-hanging mode burns thus are in many cases considerably below

the possible maximum. In the reaction mode, the listed rate sometimes occurred during the early part of the burn and sometimes during or after contact of the burning fabric with the AFMA surface.

The times to ignite cylindrical specimens of the same fabrics on the MAFT [11] are also listed. Of two fabrics with similar heat output characteristics, the one with the longer ignition time may be considered less hazardous.

Finally, table 2 shows the "reaction time," the time from the application of a match to a paper tab on the outside of the specimen to the time at which one of four sensors registered a 5° C temperature rise. Such a heat rise would probably be recognized by a reasonably alert person, who may react defensively (in the "reaction" simulation, it is assumed that the reaction leads to fabric-body contact). It is not quite clear whether a short or long reaction time is preferable. Short reaction times are generally associated with two types of fabrics: lightweight cellulosics which ignite readily and burn rapidly, and thermoplastics which melt in the flame impact area but usually burn slowly. Long reaction times are associated with heavy, thick fabrics which burn on the outside before sufficient heat is transferred to the inside to cause a reaction. Such flaming could be well developed before the heat rise is felt by a wearer in real-life situations. On the other hand, the chances of visual detection and defensive action before the skin is endangered by the heat are increased when the heat transfer to the body is slow.

For convenience in the evaluation of the relative standing of the various fabrics, the measured heat and area values listed in the columns in table 2 were classified according to quartiles; i.e., into four groups, each containing the same number of values. The quartile assigned to the numerical result is noted in the table as in the following example: 59500/3, the first entry in the total heat free-hanging column means that the total heat measured by all sensors for this fabric was 59500J and that this result is in the third (the second highest) quartile. By comparing

the quartile notations for any one fabric, one can readily establish whether a fabric ranked high in all listed properties, or, e.g., high in the free-hanging but low in the reaction mode.

In most cases, only one specimen was examined in the free-hanging mode and one in the reaction mode. When duplicates were run, results for all properties listed in table 2 generally differed by 20% of the first value or less.

3.1 Total Heat Delivered to AFMA

3.1.1 Free-Hanging Mode

As might be expected, the total heat delivered to the AFMA from fabrics when burned in the free-hanging mode generally increased with increasing fabric weight. For a given weight, the results for cotton, polyester/cotton, and the 100% acrylic fabric were similar. Blending of modacrylic with acrylic reduced the total heat delivered. The acetate woven fabric delivered less heat than the cellulosic fabrics of similar weight; the knitted acetate fabrics and the polyester and nylon fabrics were generally in the lower quartile.

3.1.2 Reaction Mode

Most fabrics extinguished soon after making contact with the AFMA in the reaction mode. These fabrics delivered considerably less heat to the AFMA in the reaction mode than in the free-hanging mode. However, in some cases, good contact was prevented by the surface characteristics of the fabric, such as the pile of the double face terry towel, No. 56, or the fabrics curled away from the AFMA surface and continued to burn, such as most acetates and acrylics (also observed by Zawistowski [8]). If the fabric continued to burn after reaction, the total heat delivered to the AFMA tended to be larger than in the free-hanging mode because of the closer proximity of the flame to the sensors.

3.2 Injury Area

Table 2 only lists the injury area for the reaction mode. In the free-hanging mode, most fabrics caused injury areas of over 80% of the total and thus there was little difference between fabrics.

The injury area did not exceed 65% of the total surface area for any of the fabrics tested in the reaction mode. The larger injury areas were generally caused by the fabrics which continued burning after the reaction, i.e., the terry towel, the acrylic knit, one acrylic/modacrylic knit, and the majority of the acetate fabrics. Relatively large areas were also found for two lightweight polyester/cotton blends which burned rapidly. At the point of reaction, most of their surfaces were already aflame and thus transferred heat over a large area. Presence of modacrylic fiber or wool in blends with nylon or polyester resulted in relatively small injury areas.

3.3 Maximum Rate of Increase of Injury Area

3.3.1 Free-Hanging Mode

The maximum rate of increase of injury area--the maximum increase in injury area measured during any 3 seconds during the burn--was highest for the lightweight cellulosic fabrics, the single and double-faced terry, the woven acetate, and the acrylic knit fabrics. It was relatively low for the nylon, polyester, and the three triacetate/nylon blends, the FR cotton, a heavy denim, two of the knits containing acrylics, and, inexplicably, one heavy polyester/cotton twill (similar fabrics were considerably higher).

3.3.2 Reaction Mode

In the reaction mode, relatively high rates were again found in the lightweight cellulosics and the acetate satin. Most other acetates were

in the middle range. Relatively low rates were again registered by the nylon, polyester/wool blend fabrics and some of the acetate and acrylic-containing knits.

In most cases, the injury rate in the reaction mode was lower than in the free-hanging mode.

3.4 Time to Ignite

Time to ignite increased generally with fabric weight for the cellulosic fabrics, except the terry towel, which exhibited a short ignition time. It was generally short for acetate and long for acrylic-containing fabrics.

3.5 Reaction Time

Reaction time also generally increased with fabric weight for the cotton fabrics. The relationship for polyester/cotton blends was similar but less regular and fabrics with a pile structure, such as terry and corduroy, had reaction times which were somewhat shorter than expected on basis of weight only. Reaction time of acetate-containing fabrics was generally in the lower quartile, indicating little time before the flames from the burning paper tab penetrated to the fabric side facing the AFMA. The acrylic group tended to be in the middle range and apparently was little affected by weight. The polyester and nylon fabrics had the longest reaction times, indicating the low heat output from such fabrics even though they were readily penetrated by the flames.

3.6 Overall Evaluation of Fabrics

The fabrics listed in table 1 are those with a low burn injury potential. While some of these ignited and continued burning, the heat developed was insufficient to cause even as little as a 5° C heat rise on one of four heat sensors on the AFMA surface. Thus, these fabrics

did not cause a reaction of the AFMA and were not brought in contact with the AFMA surface.

Table 2 lists the fabrics which caused a reaction, i.e., developed a 5° C rise and were brought in contact with the AFMA surface. They vary widely in (a) the total heat measured in the free-hanging and reaction modes, (b) injury area in the reaction mode, (c) maximum rate of increase of the injury area for the free-hanging and reaction modes, and (d) ignition time. The longer the time to ignite, the higher the probability of fabric ignition in many garment burn situations. (The other major effect on this probability of garment ignition, looseness of garment fit, is not considered here but has been discussed in an earlier paper [12].)

A review of the quartile designations for each fabric indicates that some fabrics rank high or low in all characteristics while others vary greatly in their relative positions. No attempt was made to assign a weight to these characteristics in order to develop a "hazard index," nor to evaluate relative importance of the characteristics measured in the reaction or the free-hanging modes. In every real-life garment burn, some of the garment will be free-hanging and some will come into contact with the body. The relative amount of free-hang and contact of a garment will depend on garment fit and the motion of the wearer. The AFMA reaction simulation is specific for a garment part changing from free-hanging to contact. The reaction and free-hanging simulation represent two extremes, but no prediction can be made as to their relative frequency of occurrence in real-life garment fire incidents.

The fabrics which ranked lowest in heat transferred are listed in sections D, E, and F of table 2. They had similar fiber compositions to those listed in table 1: nylon, polyester, wool, or 40-50% modacrylic. As indicated by the asterisk placed near the fabric number, many of them did not even ignite from the burning paper tab attached to the surface but ignited at the bottom edge. Their ignition times were long.

On the other end of the scale, the cellulosic fabrics weighing less than 170 g/m^2 had short ignition times and tended to be in the highest or third quartiles of the heat transfer characteristics measured on the AFMA. Also in this group were the two terry towels, which were considerably heavier. Their pile ignited in 1/2-second, and they ranked high in all heat transfer characteristics. Only their maximum rate of injury area was relatively low in the reaction mode. Apparently the outer pile burned first, followed by the rest of the fabric, resulting in high heat output burn in spite of contact with the AFMA but with the heat spreading over the AFMA at a relatively low rate.

Fabric 63 was a cotton fabric treated with a low-level of FR agent. It ranked low in total heat but quite high in the reaction maximum rate of increase in injury area and total injury area. Other investigators have found that many cotton fabrics with low-level FR treatment develop a rapidly spreading flame on the surface along a narrow path [14].

The cellulosic fabrics weighing more than 270 g/m^2 generally ranked high in total heat, free-hanging, but were in the intermediate ranking in the other characteristics, especially in the reaction mode. Apparently all extinguished in this mode upon contact with the AFMA surface.

The fabrics containing acetate or triacetate differed markedly from the cellulosics. They ignited readily and the woven acetate sateen ranked high in most heat transfer characteristics. The six other fabrics, all knits, transferred generally little heat in the free-hanging mode. In the reaction mode they did not extinguish, but the edges of the previously burned area curled away from the AFMA and continued to burn. The injury area generally did not increase in size after 15-30 seconds, but additional heat was delivered to it for up to 90 seconds. This resulted in relatively high total heat in the reaction mode. These fabrics are somewhat thermoplastic in nature, melt ahead of the flame, and shrink and shrivel in the burning area. The flame flickers considerably more than in cellulosic fabrics [8].

The heavy acrylic and polyester/acrylic knits ranked high in most heat transfer characteristics. Acrylic, like acetate, has been found to continue to burn in the reaction mode, forming a foam-like substance which does not fully make contact with the AFMA surface [8]. The lighter polyester/acrylic knit, however, ranked quite low.

4. FUTURE WORK

The flammability of fabrics discussed here has been investigated in 14 other laboratories by a variety of test methods and apparel burn accident simulations. Analysis of this extensive amount of data is in progress, with special emphasis on the apparel burn simulations on the motionless Thermo-Man, instrumented mannequin. The AFMA and Thermo-Man data will be compared with the MAFT classifications and results from our laboratory flammability tests. Consideration will be given to results of extinguishment experiments being carried out presently at NBS (measuring the AFMA heat transfer characteristics of fabrics exposed to various levels of airflow) and earlier experiments at the University of Maryland [6]. The present attempt of ranking fabrics according to flammability hazard will thus be greatly enlarged. Hopefully, the advantages and limitations of various laboratory methods in predicting these hazards will be established.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The objective of the work described here was to continue earlier garment burn simulations and to establish further background for the estimation of the relative burn injury potential of flammable apparel fabrics. The apparatus used was the Apparel Fire Modeling Apparatus (AFMA). The AFMA is a semicylinder almost completely covered with heat sensors. It simulates part of a human leg or torso. Fabrics can be burned on the AFMA in the free-hanging mode or can be brought into contact with its surface after a small amount of heat is sensed by the AFMA. The burn injury potential of the fabrics can be evaluated by such heat transfer characteristics as the total heat transferred to the AFMA and the area of the AFMA which would be susceptible to a second-degree burn, as well as the rate of increase of this injury area. The results are related to fiber content, and weight and construction of the fabrics. The fabrics used were selected from a series used in the Cooperative Program on Apparel Flammability sponsored by the American Textile Manufacturers Institute.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Accident; apparel; burn injury; clothing; fabric flammability; fabrics; fire; garments; heat transfer; injury potential; simulation.

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